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FLUCTUATIONS OF CRILLON GLACIER SYSTEM, SOUTHEAST ALASKA

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ABSTRACT

Crillon Glacier system (Lat. 58° 37′ N, Long. 137° 23′w) consisting of two long feeding arms and a common T-shaped ending along the Fairweather Fault, with two cliffed termini, has been advancing. La Perouse's sketch map in 1786 suggests that North and South Crillon Glaciers were back far enough to have separate termini in Lituya Bay, so they must have advanced at about 30 m/yr for 150 years. More detailed maps and photos show that North Crillon terminus did advance 28 m/yr into open water positions from 1894 to 1933. Some of this 4.5 km advance may well be just the result of consolidation of two long calving ice cliffs into one deep water front.

South Crillon front in the other arm of the "*T*", where no junction of fronts is involved, also advanced into Crillon Lake 10 m/yr between 1929 and 1961. This implies that the basic cause was some increased snowfall on the high mountains. At the same time glaciers from lower peaks just to the east of Glacier Bay lost nearly all accumulation by a rising snowline and receded 5 to 11 km.

Since 1926 the Lituya Bay terminus has been more or less stable where it lies in water; however, the land portion has advanced 25 m/yr since 1948. Between about 1920 and 1961 a large gravel delta appeared and grew to 145 × 10^6 m^3, so this slow ice advance on one side of the front may be due to ice shearing over the new land of the fan where ablation is slower than watercliff calving.

Prehistoric advances of Crillon Glacier system are recorded in stratigraphic deposits dated by C-14. Trees buried in the prominent extensive outer moraine system around Crillon Lake and Lituya Bay were annihilated in the maximal push of the Little Ice Age 400 to 1000 years ago. The first advance came 1500 to 1800 years ago when logs became buried in glacial outwash, now under Little Ice Age till. Because it is regional, this was a climatic event involving a lowering snowline due to cooler summers.

Still further back, in hypsithermal time, these Crillon Glacier termini were probably as retracted as today, because many outcrops of buried forest 3000 to 9000 years old occur in alluvial deposits in Lituya Bay. Underneath all these is outwash gravel and till recording the last push of Wisconsin ice, ending at least 9000 years ago. Still earlier Wisconsin advances of North Crillon Glacier carried the Lituya Bay ice tongue a little further to sea, yet all through the pleistocene, unglaciated refugia endured between the ice streams.

RÉSUMÉ

Le système du Glacier Grillon (Lat. 58° 37′N, Long. 137° 23′w), constitué par deux longs bras d'alimentation avec une terminaison en forme de *T* le long de la Faille Fairweather, et dont les deux falaises d'extrémité ont avancé. Le croquis de La Pérouse de 1786 suggère que les glaciers Grillon, Nord et Sud, étaient suffisamment en retrait pour avoir des extrémités séparées dans la Lituya Bay, de sorte qu'ils doivent avoir progressé d'environ 30 m/an pendant 150 ans. Des cartes plus détaillées et des photographies montrent que le terminus du North Grillon a avance de 28 m/an, débouchant en mer de 1894 à 1933. Une partie de cette avance de 4,5 km peut d'ailleurs être le résultat de la consolidation de deux longues falaises de glace dans un front de mer profonde.

Le front du South Grillon dans l'autre bras du *T* où ne se produit aucune jonction de fronts, a également avancé dans le lac Grillon de 10 m/an entre 1829 et 1961. Ceci implique que la cause de base a dû être un accroissement des chutes de neige sur les hautes montagnes. En même temps, des glaciers de pics moins élevés à l'est du Glacier Bay, perdirent quasi complètement toute accumulation par la montée de la ligne des neiges et recula de 5 à 11 km.

Depuis 1926, le terminus de la Lituya Bay a été plus ou moins stable la où il se trouvait en mer; cependant la partie terrestre a avancé de 25 m/an depuis 1948. Entre 1920 environ et 1961, un large delta de gravier s'est formé et s'est accru jusqu'à un volume de 145 × 10^6 m^3, de sorte que cette lente avance de la glace sur un des côtés du front pourrait bien être dû à la glace glissant sur le nouveau terrain où l'ablation est plus lente que le morcellement de l'extrémité du glacier dans l'eau. Des avances préhistoriques du système du Glacier Grillon sont établies par les dépôts stratigraphiques dont l'âge est déterminé par le C-14. Des arbres enterrés dans le système de moraines extérieures très étendues autour du lac Grillon et de la Lituya Bay ont dû être détruits pendant la poussée maximum de la petite période glaciaire, il y a 400 à 1000 ans. La première avance se produisit, il y a 1500 à 1600 ans, quand des arbres furent enterres dans les débris glaciaires. Ce fut un fait climatique comprenant un abaissement de la ligne des neiges du fait d'étés plus froids.

Encore avant, les terminus des Glaciers Grillon étaient probablement aussi contracté qu'aujourd'-

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hui, car de nombreux arbres de forêts enterrées, vieilles de 3000 à 9000 ans se retrouvent dans les dépôts alluviaux de Lituya Bay. En-dessous de ces dépôts, se trouve des graviers marquant la dernière poussée de la glace du Wisconsin qui prend place il y a au moins 9000 ans. Encore plus tôt, des avances des la glace du Wisconsin du North Crillon Glacier porta la langue de glace de Lituya Bay un peu plus avant dans la mer, des refuges non couverts de glace subsistant entre les courants de glace tout au long du pleistocène.

BACKGROUND

Crillon Glacier, unlike a majority of northern hemisphere glaciers, has expanded slowly during the last two centuries. Yet its prior history since late Wisconsin time parallels that of most larger southeast Alaskan glaciers. A field study in 1961 was designed to get evidence from historic markers, glacial stratigraphy, and carbon 14 dating. The analysis in 1962 indicates why these changes took place and why some Alaskan glaciers advanced in the last century while the majority retreated.

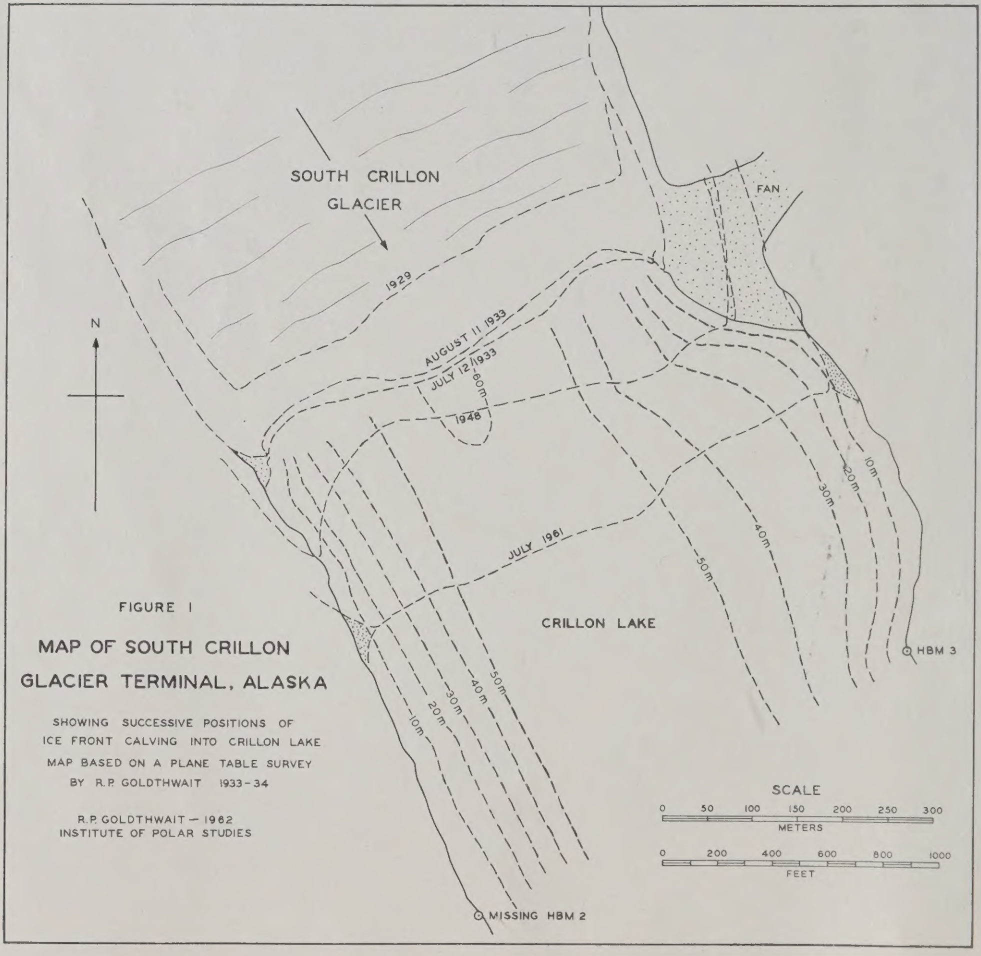

FIGURE 1

MAP OF SOUTH CRILLON GLACIER TERMINAL, ALASKA

SHOWING SUCCESSIVE POSITIONS OF ICE FRONT CALVING INTO CRILLON LAKE
MAP BASED ON A PLANE TABLE SURVEY BY R.P. GOLDTHWAIT 1933-34

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The area is on Alaska's southwest "outer" coast, 200 km west of Juneau, and just across southern Fairweather Range from Glacier Bay. The Crillon Glacier system arises from ice fields and cascading glaciers 800 m to 3500 m above sea level on the west side of Mt. Crillon (3880 m). It consists of two parallel valley glaciers flowing west 8 km and then turning right angles in "T" shape into the very long deep trench of the active Fairweather Fault (Fig. 4). Ice in lower North Crillon Glacier turns northwest for 4 km to form the tidal terminus in Lituya Bay; ice from South Crillon Glacier splits, some flowing alongside North Crillon Glacier 5 km to the land portion of terminus in Lituya Bay, and some south to a spectacular ice cliff in Crillon Lake (96 m). This is a region of heavy precipitation from the adjacent Pacific Ocean (estimated at 200-500 cm/yr based on summer rains) and frequent storms generated by the Aleutian "Low". Firn limit is just above 900 m. A review of photos on the Harvard-Dartmouth Expeditions in 1933-34 suggests an annual net accumulation of 10 m snow above 1500 m, and recent exploration drilling in Brady Glacier across the range demonstrated 3 to 8 m net accumulation much lower down.

North Crillon Glacier was first recorded in July 1786 by a longboat party under J.F.G. LaPerouse. The adjacent Crillon Arm was sounded and sketched. The first navigation chart was compiled by U.S. Coast Survey in 1874 and an early map was made by Alaska Boundary Commission in 1893. It has been visited by fishermen, prospectors, and mountain climbers throughout this century. The U.S. Coast and Geodetic Survey completely remapped it in 1926, 1929, and 1958. A climbing party under H.B. Washburn, Jr. made the first ascent of South Crillon Glacier in 1930 and the senior author conducted a scientific party out of Crillon Lake with the Harvard-Dartmouth Expeditions of 1933 and 1934 (Washburn 1936; Goldthwait 1936). During World War II and again from 1952 to 1958 U.S. Geological Survey parties mapped bedrock in this area (Miller 1961) and studied the amazing effects of the water wave generated by the 1958 and earlier earthquakes on Fairweather Fault (Miller 1960). New glaciological data were collected from June to August 1961 by a group of five under the senior author, based at Cenotaph Island in Lituya Bay with a one-month camp on Crillon lake. The National Science Foundation (grant no. G-16023) supported the project, National Park Service supplied local transport, radio and equipment, and The Ohio State University assisted with five radiocarbon analyses. Other articles concerning the Pleistocene stratigraphic history and the generation of deposits below Klooch Glacier are in preparation.

HISTORIC CHANGES

South Crillon Ice Cliff

Precise mapping of South Crillon ice cliff goes back only to the air photography of 1929. Since this time the terminus has presented a spectacular calving cliff 500 m to 600 m long and 25 m to 50 m above water. Soundings by lead line in 1933 indicated water depths up to 50 m and 60 m, making the ice 110 m thick at maximum (Fig. 2). The flattish bottom is 200 m broad, which, along with the 37° cliff and talus slopes on either side, forms a fine U-valley nearly 1000 m deep. So uniform is this deeply glaciated trough that the ice front today looks just like that of 1929.

Eight records were made in 32 years:

July and August 1929	U.S. Forest Service Aerial Photographs.
July 21, 1933	Plane table surveys by the Mt. Crillon Expedition (*)
August 11, 1933	
August 6, 1934	
1948	Vertical Aerial Photographs.
August 29, 1958	Nine lens Aerial Photographs by U.S. Coast and Geodetic Survey.

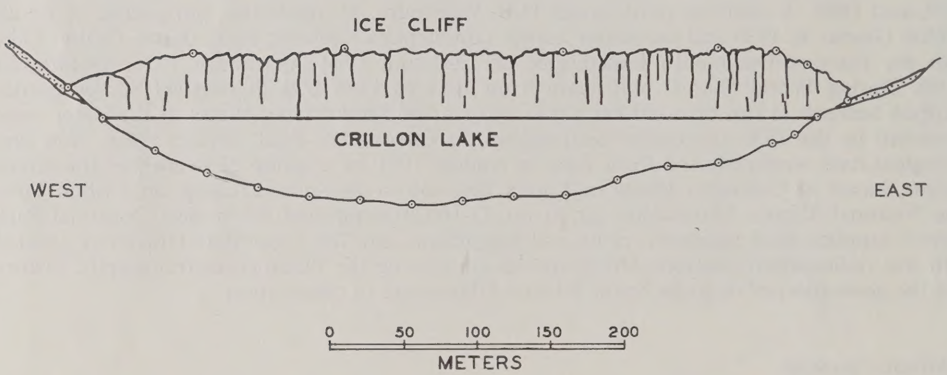
(*) Of the four "Harvard Bench Marks" set in along the shore south of Crillon Ice Cliff in 1934, two were over-ridden by 1961, and only one (*HBM-3*) could be found above water.

August 1959	Vertical Aerial Photographs, U.S. Coast and Geodetic Survey.
July 1961	Theodolite angles and photographs obtained during present expedition.

On the map (Fig. 1) the advance appears to be regularly continuous at the rate of 10 m/yr totaling 300 m to 350 m in 32 years. The northeast end advanced a little more than the southwest one. Actually, as the two mappings in 1933 suggest, this advance consisted of a series of long winter advances offset by lesser retreats each summer. This is because of ablation of the terminus is by warm water calving between mid-June and late-September. If the retreat of the warmest 20 days totaled nearly 11 m certainly the total summer net retreat phase amounts to more than 30 m.

FIGURE 2
PROFILE OF TERMINUS OF
SOUTH CRILLON GLACIER

MEASURED ON AUGUST 11, 1934 BY
R.P. GOLDTHWAIT



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When remapped in 1961, both sides and the terminus of the glacier showed signs of having been more advanced in 1959 or 1960. Trees pushed over a year or two before (with brown needles) marked the outer lateral moraine deposits, yet the ice surface already had retreated 50 m in mid-July. We infer, as one might expect, that the advance of South Crillon Glacier has not been uniform every year, but more some years (1959) and less or negative in others (1961).

Character of ice motion

The absolute motion of the ice surface has been carefully measured at mid-summer in 1933, 1934, 1936, and 1961. In 1933 a stake in midglacier 1 km north of the terminus was aligned with a flagged spruce on the opposite wall, and the motion over 28 days averaged 62.7 cm/day. Theodolite measurement of ice pinnacles near the cliff varied 46 to 104 cm over 3 days. In 1934 and 1936 a lighted marker 0.5 km from the terminus, observed by a theodolite from a rock wall station, moved 70.6 cm/day and 60.4 cm/day over 6½ and 20 days (Washburn and Goldthwait 1937). In July 1961 the fastest natural feature, 2 km from the terminus, measured by theodolite (Cronk, McKellar and Haselton) moved 84 cm/day. Two-day measurement of objects within 200 m of the ice cliff gave only 46.8 cm/day and 54.0 cm/day. This indicates the average advance of ice in all parts of South Crillon ice cliff is at least 0.4 m/day or 145 m/yr. If the net advance of the ice cliff position is only 10 m/yr in round figures, the annual total calving rate is 135 m/yr.

Discharge of this glacier into Crillon Lake involves 6.65 × 10^6 m^3/yr based on the recent cross section (Fig. 2; 50,000 m^2). Icebergs from the exposed upper half of the glacier accounted for nearly half of the discharge which was recorded in a qualitative way, in 1933, when all large and small ice falls were noted at camp 1.3 km away. It became clear on all visits that at least half of the activity occurred in the quarter of the day just before and after sunset, with added activity just after midnight and 8-9 a.m. (Washburn 1936). Since the undercutting of ice is greatest just below waterline it is suggested that this is in response to direct water circulation of the heat influx of the day.

Diurnal variation in calving might be due in small part to variation in motion. In 1934 it was shown that "several periods occur during the course of a day, when motion is faster than at other times". These periods included late afternoon and "shortly after midnight" but also involved 8 a.m. and noontime. In 1936 "At least three, and usually four, periods of especially rapid motion were recorded each day". "In general, all bi-hourly graphs seem to show periods of greater motion shortly after midnight, about 7:00 a.m., and 2:0 p.m. and again early in the evening". "The two night periods and that which occurred between 6:00 and 8:00 a.m. occurred consistently". (Washburn and Goldthwait 1937). This has been challenged on the grounds that there is diurnal instrument drift in any fixed theodolite. Also half-day total motions were slightly greater during daylight in 1934.

	Day	*Night*
	6 a.m. to 6 p.m.	6 p.m. to 6 a.m.
July 17, 1934		34.4 cm
July 18, 1934	36.3 cm	39.6
July 19, 1934	40.5	40.8
July 20, 1934	41.5	41.9
July 21, 1934	44.5	42.9

When checked in 1961 by a two-day measure of two boulders near the midterminus, the night motion was 38 percent less than the adjacent days.

	Day	*Night*
	7 a.m. to 7 p.m.	7 p.m. to 7 a.m.
Point 1, 733 m from inst.		
July 26, 1961	19.2 cm	17.1 cm
July 27, 1961	27.4	
Point 2, 648 m from inst.		
July 26, 1961	20.4	20.4
July 27, 1961	37.4	

One can only conclude that the pattern of diurnal motion needs longer investigation, but discharge does concentrate toward the close of each summer day.

Not so questionable is a correlation with the weather. In 1934 the "ice mass flows faster during warm sunny weather than when the sun is overcast" and the "minimum of movement is reached during a cold rainstorm". Again in 1936 "Definite response is shown to rainy or sunny periods" (Washburn and Goldthwait 1937). Unfortunately in 1961 only two days were measured, but this was the end of a long clear sunny period and both boulder points measured had accelerated by 35 percent or more from 26th to 27th July.

North Crillon Glacier terminus

This glacier was recorded in the first white exploration of Lituya Bay, led by Jean Francois LaPerouse in 1786. He entered Lituya Bay with two square riggers on July 13, 1786 and within a few days the right (southeast) arm of the T-shaped bay had been sketched and sounded by Monneon and Bennizet (Flory 1927). They showed what is apparently North Crillon Glacier as a separate front on the east side of the arm and South Crillon Glacier touched it in a continuing curve, blocking the south end of the bay (Fig. 4). The bay was 6.4 km long. The map is rough but the outlines of the bay fit modern coast charts so well that we may be quite sure that the ice was 4.3 to 4.9 km back of that today.

The advance which ensued was recognized by members of the Canadian Boundary Survey in 1893-94 (Klotz 1899). In the century before this first precise survey, North Crillon Terminus had advanced 2.9 to 3.5 km at a possible rate of 27 m to 32 m per year. The rate may have been even greater since most advance took place after the first "Coast Pilot" description was published in 1884. The advance was that of an ice cliff into water 80 m deep.

July	1786	LaPerouse exploration sketch map.
	1884	U.S. Coast Survey description.
	1893	Alaska Boundary Commission triangulation and
	1895	photographs.
	1926	Aerial photographs and triangulation for Coast and Geodetic Map of 1929.
Aug.	1929	U.S. Navy air photographs.
Aug.	1933	Harvard-Dartmouth Expeditions triangulation,
	1934	oblique photos, plane table and aneroid.
Aug.	1948	U.S. Navy air photographs, used in map by Miller 1960.
Aug.	1958	Air photographs, retriangulation (1959) by U.S. Coast and Geodetic Survey, map 1962?
Aug.	1961	Triangulation from 1959 U.S. Coast and Geodetic benchmarks by present expedition.

The first U.S. Coast and Geodetic Survey navigation chart (#3505 of 1929), based on 1926 airphotos, fits well by landforms to the 1895 boundary maps, and shows an advance continuing for 32 years at an average near 16 m to 19 m per year. The cliff front shown smoothly-curved on earlier charts then became ragged. The west corner had just become grounded on a rapidly growing outwash-delta. This advance continued at the average rate of 43 m/yr at least up to the Harvard-Dartmouth Expeditions of 1933-34 (Washburn 1936) although the terminus on the delta advanced not over 100 m (14 m/yr) total in contrast to the 500 + m (71 m/yr) on the east margin of the terminal (Fig. 3).

This marked the close of the long advance. Because the advance persisted for a century and a half, one can justly infer a climatic effect. If so, this must have been increased snowfall at high altitude, because during the same period of time (Vancouver exploration of 1794, to first precise map by Reid in 1892, to Field's map in 1929), Muir Glacier 75 km to the east retreated about 300 m/yr. This is known to be due to rising firnline (Field 1947) and warming temperatures. The only major difference between the two glaciers is that the Muir Glacier system arises in low mountain divide near 2000 m whereas Crillon Glacier system starts from plateaus above 3000 m. Indeed the adjacent small Cascade, Lookout, and Klooch Glaciers which arise at 1500 m have shrunk while their larger Crillon neighbours advanced. This suggests that as firnline rose on the high Fairweather Range and mean annual temperature increased, the precipitation also increased, elongating only the glaciers which feed at high altitude. Mercer (1961) has shown that the precipitation at coastal stations did increase.

There is another important reason for advance. If due to other causes two long ice cliffs such as South Crillon and North Crillon Glaciers on LaPerouse's map become one consolidated single front of half the combined former length, the total ablation rate by warm sea water is cut in half. This allows the glacier to thicken, firnline to advance, and the ice cliff to advance markedly to where it broadens or expands (Mercer 1961). Whether this one factor

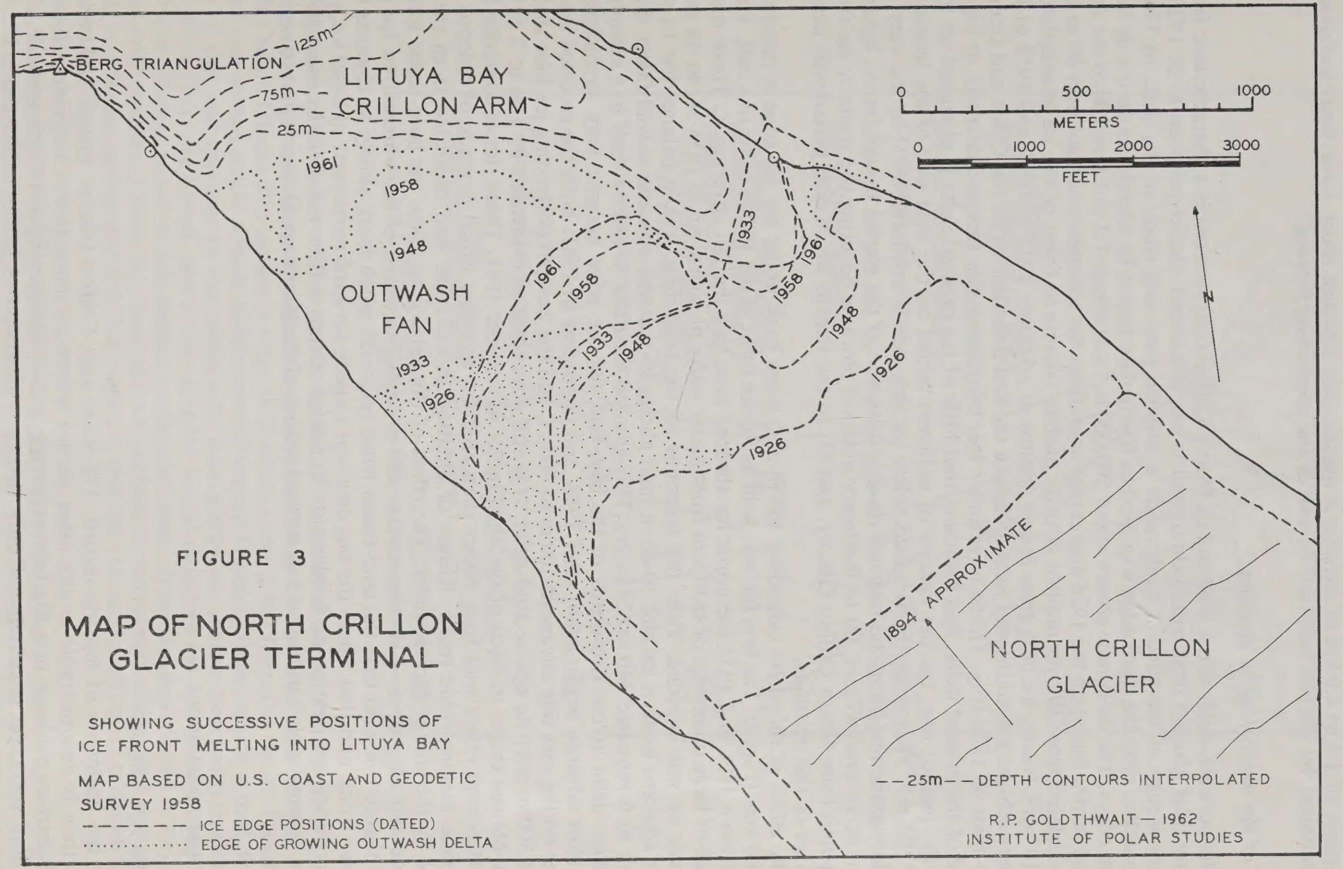

FIGURE 3

MAP OF NORTH CRILLON GLACIER TERMINAL

SHOWING SUCCESSIVE POSITIONS OF ICE FRONT MELTING INTO LITUYA BAY

MAP BASED ON U.S. COAST AND GEODETIC SURVEY 1958

------ ICE EDGE POSITIONS (DATED)

.... EDGE OF GROWING OUTWASH DELTA

--25m-- DEPTH CONTOURS INTERPOLATED

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will explain all 4.3 to 4.9 km of advance is questioned; advance must have been instigated if not continued by heavier snowfall as well as the combining termini.

Effect of the outwash-delta deposits

The outwash-delta at the west end of North Crillon Glacier front is a characteristic feature of many tidal glaciers near equilibrium, and it has influenced glacier advance since 1926. To gain knowledge of the effect, Cronk made a detailed map and study of the delta in 1961. A 95 m baseline near the distil edge was used to triangulate points by theodolite up the delta and on both edges. The delta now covers about 500,000 m^2 and slopes 1.3 to 1.0 m/100 to the northeast and north. Based on the 1926 and earlier soundings the sediment averages over 80 m deep, and calculated from the yet unfilled bottom profile, volume in front of the ice is calculated at 97 $\times$ 10^6 m^3. Nearly all of it grew in two spasms of addition: 1933 to 1948, and 1958 to 1961. This outwash-delta is additional to and beyond the first delta shown on the Coast and Geodetic Survey map of 1926 (Fig. 3) but now under ice. Estimating this former first delta at half the volume of the present delta, and assuming that little of the original delta is ploughed up by ice under the present one, the net volume of sediment added on the west side of the terminus is 145 $\times$ 10^6 m^3. That it has been added solely on this side is attributable (1) to the very fractured low-grade metamorphic bedrock on this west side of the glacial trough (talus, landslide, and fan occur everywhere), (2) to the heavy ablation moraine covering the westerly ice stream contributed from South Crillon Glacier, and (3) to the stream which exits persistently near the west edge of the terminus.

The effect of this delta extending 500 m and more back under the ice edge is interpreted from the map (Fig. 3). The first fan was built as the ice front of the 1920's came to a halt. However, between 1926 and 1934 the upper ice sheared over half the fan covering it. There was no evidence of large quantities of sediment from under water ploughed up in 1933-34, so we expect the lower ice was impeded. Then this terminus on the land delta was in balance for 14 years but the adjacent eastern ice cliff 30-40 m high above 40 fathoms of water calved faster than it was fed, so it retreated 340 m (24 m/yr). This allowed the delta to extend itself in a completely new larger delta across two-thirds of the bay, and the ice edge became very asymmetrical. When slow advance began again after 1948, and continued to 1961, both the recessed ice-cliff in water on the east side advanced 100 m to 300 m, and the western protruding ice lobe sheared at least 300 m over its new second delta. It is still advancing as evidenced by 1 m to 2 m high sharply-plowed ridges in front of the ablating ice in summer 1961. These ridges comprise fractured Mesozoic valley wall rock rather than ablation moraine which is made of igneous and high grade metamorphic rocks. Ridges of ablation moraine are also deposited from the 45° ice face by the end of each summer. The effect of the delta is to allow the land-based lobe to protrude and advance as a sloping surface 300 m to 400 m ahead of the watercalved ice cliff. It is probably true also that the land-based front responds much more slowly to changes than the water front, and that where the fan does not impede forward movement of basal ice, reactions to minor acceleration or deceleration in the ice stream will be reflected. In effect the ice cliff is a "prematurely" truncated free vertical section of the glacier which reacts first to regimen change.

PREHISTORIC CHANGES

Little Ice Age Advance

At the beginning of historic record, 178 years ago, Crillon Glacier system had receded further than is demonstrable in any other period before or since. It was surprising, then, to get radiocarbon evidence that the last prehistoric glacial advance equalled any advance in the last million years, yet it culminated only two to three centuries before exploration, i.e., 390 to 600 years ago.

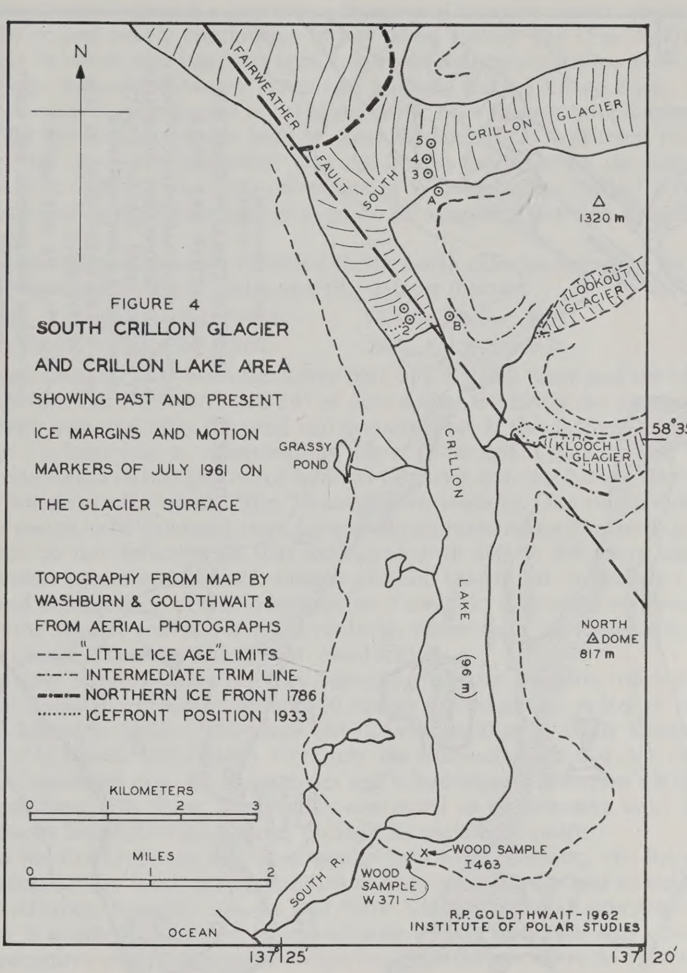

FIGURE 4
SOUTH CRILLON GLACIER AND CRILLON LAKE AREA
SHOWING PAST AND PRESENT ICE MARGINS AND MOTION MARKERS OF JULY 1961 ON THE GLACIER SURFACE

TOPOGRAPHY FROM MAP BY WASHBURN & GOLDTHWAIT & FROM AERIAL PHOTOGRAPHS

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High up on the slopes around Crillon Lake (220 m to 500 m above) and blocking its extension south is a prominent continuous morainic system (Fig. 4). The outermost limit of ancient South Crillon Glacier lies against a ridge of Tertiary rocks 2 km from the Pacific Ocean. The glacier also spread out in a bulge southeastward toward Dagelet Glacier which it then abutted. West of this end moraine to the ocean only inter-glacial cut marine benches (Heusser 1960 and Miller 1961) are found. Above the stranded lateral moraines (to 490 m on Grassy Ridge and North Dome) on either side there is unglaciated open alpine meadow devoid of any transported drift or striae. Unless very ancient drift has been so completely obliterated that pointed search by a dozen geologists has failed to spot it, this was the maximum extent of South Crillon Glacier for all time.

There are two C^{14} dates:

W-371, 3 m depth, D.J. Miller (1953)	390 ± 160 yr. B.P.
I-463, 20 m depth, R.P. Goldthwait (1961)	600 ± 125 yr. B.P.

Both were fresh spruce logs exposed by a landslip lying prone under till in the terminal

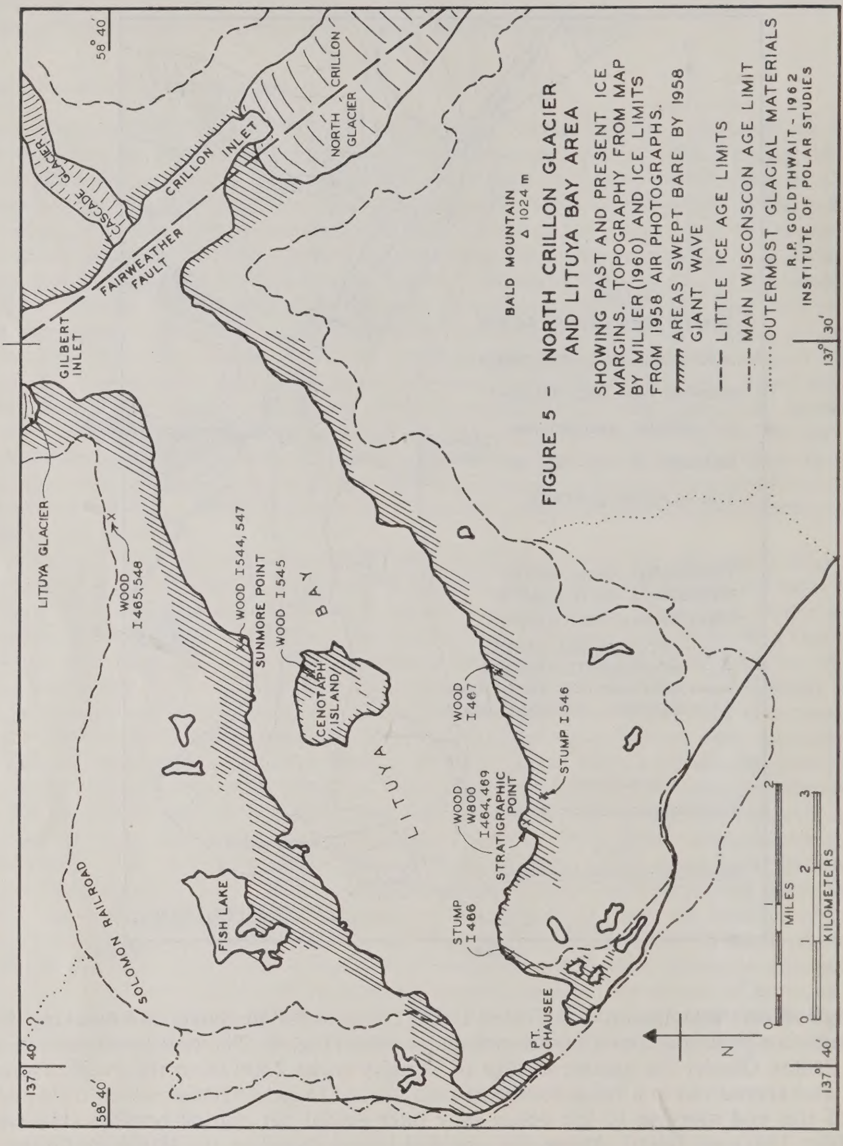

FIGURE 5 - NORTH CRILLON GLACIER AND LITUYA BAY AREA

SHOWING PAST AND PRESENT ICE MARGINS. TOPOGRAPHY FROM MAP BY MILLER (1960) AND ICE LIMITS FROM 1958 AIR PHOTOGRAPHS.

▨ AREAS SWEPT BARE BY 1958 GIANT WAVE
— — LITTLE ICE AGE LIMITS
—·—·— MAIN WISCONSON AGE LIMIT
.... OUTERMOST GLACIAL MATERIALS

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moraine system. Miller felt that these trees grew nearby. The younger sample was 0.6 km east of Crillon Lake outlet and only 3 m below the top of the slip (Rubin *et al*, 1958), and the older sample was 1.0 km east of the outlet but in a gravel lens and tangle of logs about 20 m deep. The curve and continuity of the moraine clearly relate it to Crillon (not Dagelet) Glacier system; the condition of the wood, bark, roots, and the time restriction itself, make redeposition unlikely. There is no higher adjacent ground from which the landslip might occur. Since these logs represent the upper parts of the moraine, (over 130 m above Crillon Lake) they clearly indicate completion of the moraine not more than 400 to 600 years ago in The Little Ice Age.

In a similar situation there is a prominent lateral-end moraine system above North Crillon terminus at 560 m and nearly continuous 11 km down Lituya Bay (Fig. 5). It is so striking and regular that its north arm has long been known as Solomon's Railroad. West of the deep fjord-pass through the coastal ranges it enlarges laterally from 3 km to 8 km. Unlike Crillon Lake, this is not quite the outermost and highest drift; near the seashore Lituya Bay is ringed by an even wider but less-prominent bulb of older Wisconsin (?) drift from Portage Creek to Whale Creek. This raises the possibility that the lateral moraines up the main fjord, which are the highest drift (400 m), may be a composite of Wisconsin plus Little Ice Age deposition. Indeed one C-14 date (see I-465 below) in sand on till suggest a moraine-dammed pool before 2600 years ago.

The high east end of Solomon's Railroad on the north side has been well dated. Two prone logs exposed by a landslip, but *in situ* under till, date as follows:

I-548, 9 m depth, R.P. Goldthwait (1961)	1090 ± 100 yr. B.P.
I-465, 12 m depth, I.C. McKellar (1961)	2600 ± 160 yr. B.P.

The younger sample came from the lower part of a 5 m till layer and the upper one came from sand below an 8 m till layer, both 345 m above tide. Evidently the upper till was laid by a readvance many centuries after the sand had accumulated. If this farthest advance took place 1100 years ago (or later due to redeposition) this may be called part of The Little Ice Age. Confirmation was found in stumps rooted in till at tide level in lower Lituya Bay near the broad looped end of Solomon's Railroad ("Bay" triangulation station). One stump dated 1025 ± 100 B.P. (I-466). It seems to be exhumed out of overlying moraine deposit by present waves.

These dates do not demonstrate that ice stayed until 400 to 600 years ago as at Crillon Lake, but common source and climatic history demand that it did. In addition the size of the present trees and composition of the forest (spruce, hemlock) within the confines of Solomon's Railroad Moraine suggest growth for a few centuries rather than the thousands of years necessary for the tall senile forests outside (cedar, hemlock).

There are only limiting dates for the beginning of the invasion during the Little Ice Age. Proglacial outwash gravels under the till veneer are common. A log in the outwash on east Cenotaph Island is 1800 ± 160 years old (I-545), another at Gully Creek on the south shore is 1525 ± 125 years old (I-467). Certainly the advancing ice had not reached halfway down the bay 15 centuries ago. By 10 centuries ago it had topped Solomon's Railroad and reached its seaward limit, The Paps. It probably continued to be extensive until 3 centuries ago when the confluent South Crillon Glacier finished its maximum push.

The cause for the Little Ice Age is generally held to be climatic, viz: lower temperature and heavier precipitation. Since precipitation is already near 400 cm and seems to be the cause of the present advance, one may suspect that Little Ice Age snowfall was about the same. As a hypothesis it is suggested that the major advance of the Little Ice Age was due primarily to cooler temperatures which lowered snowline by the order of 500 m to 1000 m.

Hypsithermal advances, or protracted retreat?

The question arises, was there a prolonged retreat or were there other ice advances prior to the Little Ice Age? For North Crillon Glacier down Crillon Inlet and Lituya Bay we have some answer. Logs buried in sand on top of stranded lateral moraine (I-465) show that some moraine was there 2600 years ago, but they hardly prove presence of ice. Similarly, 0.5 km east of Edrie survey station (Stratigraphic Point) on the mid-south shore of Lituya Bay, all the small sruce stumps in a recently exposed buried forest lean toward the sea, as though annihilated by advancing ice; they date back to 3040 ± 150 years ago (I-546). However, the stumps in place are buried by 0.5 m to 1.2 m of sorted sand. Till or boulders rest only on the broken tops. They may easily have been truncated by the Little Ice Age advance many centuries after burial. There is no good evidence of earlier advance.

There is more positive evidence of long periods of inter-stadial alluvial-lacustrine sedimentation. On Stratigraphic Point (Edrie survey station) on the south shore of Lituya Bay, three levels of buried forest are exposed one above the other:

Upper — covered by 1.0 m of Little Ice Age till	6060 ± 200 years (W-800) or 6250 ± 200 years (I-464)
Middle— covered by 1.9 m lacustrine silt-sand	not dated
Lower — stumps covered by 0.6 m coarse sand	7460 ± 200 years (I-469)

On Sunmore Point on the north shore are also three different age levels:

Upper — forest covered by 3.5 sandy gravel and 1.4 m till	8925 ± 250 years (I-544)
Middle— scattered woody zones covered by 2.1 m sand	not dated
Lower — stumps covered by 2.3 m cross-bedded sand	9150 ± 275 years (I-547)

Clearly there was no ice and a lower sea level most or all the time from 6000 to 9000 years ago. Alluvial streams and fans were common to within 5 km of the present glacier termini.

The ice fronts in this hypsithermal time cannot be located. We know only that they were not near enough to the most easterly stratigraphic deposits (Coal Creek and 1 km east of Sunmore Point) to supply coarse outwash gravels. They could not have been more than 1 km to 3 km more advanced than they are now, and might have been receded a few kilometers.

Wisconsin Glaciation

The next earlier major ice thrust was that of late Wisconsin time. Excavation to 6 m below the forest layers of Stratigraphic Point uncovered gravel which was coarsest near the base. The same is true at Sunmore Point, suggesting that late Wisconsin outwash (mixed pebble types from interior) immediately underlies the hypsithermal forest beds; here also there is till. Obviously it must predate the 9150 B.P. forest which it underlies, but no specific dates were obtained. This agrees with dates back to 10,000 years for the close of Wisconsin glaciation in southeast Alaska (Heusser 1960).

That Solomon's Railroad moraine was formed in large part by the Wisconsin ice is suggested by its very massive size if not by the pre-Little Ice Age accumulation on it. Earlier in Wisconsin time, however, North Crillon Glacier spread even further seaward, as clearly shown by the low end moraine leading into Harbor Point and Point Chausee at the mouth of Lituya Bay. The till at tide level in which drowned stumps 10 centuries old (I-466) are rooted must represent this advance. No carbonaceous material could be found to date this earlier Wisconsin advance.

Separately and earliest of all, the ice spread way out to sea, for 11 km of the Pacific Coast — from Whale Creek to 1 km northwest of Portage Creek — is littered with huge granite boulders from the interior Fairweather Range. Low moraines and outwash in the woods are not weathered more than Wisconsin drift elsewhere, so it is proposed that this is the earlist and greatest spread of Wisconsin drift. These three advances of North Crillon Glacier in Wisconsin time are not registered at all in the South Crillon-Crillon Lake trough, for the Little Ice Age drift has masked everything.

As the geological mapping by Miller (1961) suggests, and as specific search by the authors showed, there is no evidence that ice has ever covered or been higher on the Coast Range (Bald Mountain and Grassy Ridge) here or on the lower peaks such as North Dome. Although these driftless areas are separated from others by the former broad ice tongues of LaPerouse Glacier, North Crillon Glacier (Lituya Bay), and Fairweather Glacier, these constituted important refugia for plants and animals all through late Pleistocene time. The age of forests is limited only by Pleistocene interglacial higher sea levels.

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